A NEW MOBILE AND COST-EFFICIENT INDUSTRIAL DRYER FOR SLUDGES DRYING TO PROMOTE STEEL INDUSTRY MATERIAL EFFICIENCY

Virpi Leinonen, Jani Isokääntä, Juha Roininen - SFTec Oy, Paavo Havaksen tie 5D, FI-90570 Oulu, Finland

From steel industry, many kinds of wet by-products are landfilled. These wet streams usually contain valuable materials like metal oxides and carbon. For example, steel industry sludges are normally composed of metal oxides with very fine particle size and high-water content. The major problem with sludges is that they have a moisture content of around 25 to 35 % and their physical properties are difficult for traditional dryers to handle. ModHeat (Modular Heating) is a modular and mobile industrial dryer innovated and patented by SFTec Oy (Finland), which enables economical and efficient utilization of unused industrial waste heat to dry waste materials such as sludges. Pilot and full-scale pilot tests with ModHeat dryer have showed that it enables drying of these wet, hard to handle materials within optimal sufficient low temperature (under 100 °C), in reasonable time. The adhesive nature of sludges did not hinder drying and the material moved in the process as planned. After drying these material streams could be reutilized and valuable materials recovered. ModHeat is an important innovation for this sector as it will increase the material efficiency and recovery.

KEYWORDS: SLUDGE, INDUSTIRAL DRYING, MATERIAL EFFICIENCY, MODHEAT, WASTE HEAT

INTRODUCTION

Steel as a recyclable product is an environmentally friendly choice as a material in many applications. Currently still part of the main side streams of steel production is disposed and most of the all energy in ferrous slags is wasted, when slags are cooled down. As a part of the steel production the side stream handling and zero-waste targets are the aims of global steel industry to compete in the competition of materials. Environmentally friendly and more ecological steel production is the future target. Energy recovery and reuse of side streams as a valuable product are ways to minimize the ecological footprint of steel production. To achieve these targets, one must have cost-efficient technologies to treat the low value materials and recover and utilize the collected *waste* energy streams. As a one option and solution to increase the energy- and material-efficiency of steel production is an innovative drying technology ModHeat (Modular Heating) developed by SFTec Oy, Finland.

At the moment, there are no suitable and cost-effective dryers available for drying steelmaking sludges and other wet side streams, as the drying is a highly energy intensive process and materials are hard to handle. It is cheaper to landfill the sludges than to dry and utilize the solids, even though landfilled sludges cause environmental impacts and costs. Drying of the sludges enables recycling of valuable materials like iron oxides and carbon from the landfilled materials. Increased material recycling saves primary raw materials, and at the same time decreases the need for landfills.

Utilization of waste heat is challenging, because of its variable availability. At every steel mill area, many kinds of discontinuous hot steams (80 - 200 °C) and cooling waters (60 - 90 °C) are being generated. Nowadays available heat transfer and traditional drying technologies are unable to utilize these existing discontinuous waste heat streams cost-effectively.

Drying and utilization of “low value” by-products and the loss of energy in cooling of the slag are critical problems in metal industry to be solved. SFTec enables a technological solution for these problems by novel drying technology that can also use energy recovered from the slag cooling. Energy and material efficiency can be increased by utilizing waste heat and increasing internal recycling (e.g. sludges and scales). The steel industry has been chosen as the first market segment for the ModHeat dryer, because this segment has huge amounts of unused waste heat available and many different kinds of by-products such as sludges are still without an economical drying solution.

1. INDUSTRIAL DRYING

In several industrial sectors, and in processing of different kinds of side streams or by-products, drying is perhaps the most common unit operation needed. Several different types of drying technologies are available for different kinds of materials and needs. Drying is also one of the most complex, but still least understood process at the same time. Drying includes simultaneous and coupled heat, mass and momentum transport in the matter media. Even though of complex nature, the simple target of drying is to reduce the moisture content of the dried material for different purposes to enable materials further use or processing. [1]

In direct convection dryers, like ModHeat technology, the heat media is in contact with the material. For pasty and particulate solids convection is one of the most common mode of drying. Energy is transferred as heat from the heated air to the wet material. Heat transfer can occur as a result of convection, conduction or radiation and in most cases as a result of a combination of these effects. The exposed surface of the material is heated up by convection for evaporation and the evaporated moisture is carried away by the drying medium. [1,2]

Drying is an energy intensive process, as the latent heat of water vaporization (eq. 1.) is the requirement for all the vapor that is removed. The latent heat of vaporization of water is [3]

$$H_2O\ (l) \rightarrow H_2O\ (g) \qquad 2260\ kJ/kg_{H2O} \qquad (1)$$

Energy need for drying depends also on the material specific heat capacity (c_p), ambient conditions, technology and moisture content of the media. The key of drying is how much moisture (kg_{H2O}) needed to be evaporated per time unit. By measuring the moisture content loss as a function of time, the drying behaviour of solids can be characterized. Measuring methods used are humidity difference, continuous weighing and intermittent weighing. [2]

Drying rate of the material varies depending on material properties. In Fig. 1 shown schematically the various types of characteristic drying curves. In figure 1 picture A and B are examples of the drying rate curve of a sand and clay type of materials, which reflect metallurgical sludge drying. Form of the drying rate curve shows that at first energy is used to warm up the material and after that drying proceed with quit constant rate, as the solid material mainly contains free water to be evaporated. During the constant rate period, the rate of drying is determined by the rate of evaporation. After all the exposed surface of the solid is dry, vapor movement by diffusion and capillary from within the solid to surface are the rate-controlling steps. [2]

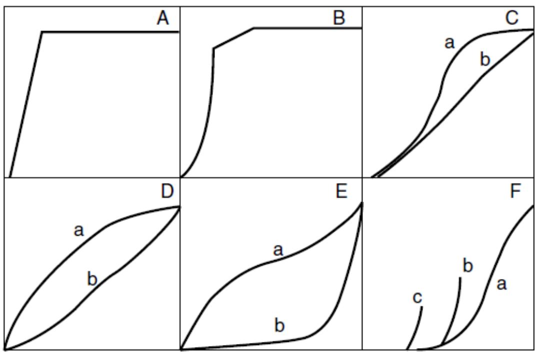

Fig. 1. Normalized drying rate curve examples for different types of medias [2].

In convectional drying the amount of air and air velocities are important parameters affecting to the drying rate. Air velocities are important to the extent to which they enhance heat transfer rates in the drying process. Air temperature, humidity, material thickness and bed depth all become important factors in evaluation of the whole drying process. [2]

In solid materials like metallurgical sludges, moisture can be in a solid either unbound or bound. Unbound moisture may be removed with two methods: evaporation and vaporization. Evaporation is done by raising the temperature of moisture to the boiling point. It occurs when the vapor pressure of the moisture on the solid surface is equal to the atmospheric pressure. In vaporization, drying is carried out by convection. Convection is achieved by passing warm air over the product. With air and product contact, the air is cooled by the product, and moisture is transferred to the air by the product and carried away. In vaporisation, the saturation vapor pressure of the moisture over the solid is less than the atmospheric pressure. Vaporisation occurs with lower moisture vapor pressure than atmospheric pressure and at low temperature (T_{H2O} < 100 °C). Also, relative humidity (RH) and water partial pressure ($p_{H2O(g)}$) effect to the vaporisation. Relative humidity describes the level of saturation of air and its capacity to carry out the moisture. [1,2]

External conditions are important to the drying of unbound surface moisture. The main effecting conditions are temperature, humidity, rate and direction of airflow, physical form of solids and agitation. On the other hand, internal conditions such as diffusion, capillary flow, closed porosity, internal pressures and shrinkage, vaporization and re-condensation to exposed surface are important for bound internal moisture drying. [2] In Fig. 2. shown forms of water distribution in a material media.

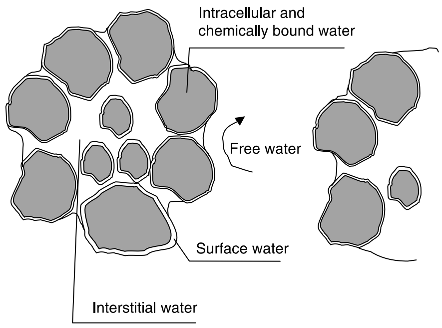

Fig. 2. Water distribution in material media [2].

Drying is highly material specific process and many difficulties are seen in the selection of dryers. The main difficulty is that there is no standard set of systematized laboratory tests using standardized apparatus to provide key data on the drying characteristics of materials. The real mechanics of liquid removal from the solid is very material specific, which makes it even more difficult to measure and understand. There is also a lack of reliability to scale up laboratory data and even pilot-plant data of dryers for industrial scale use, which has led to the fact that it is always wise to run preliminary tests to ascertain both design and operating data. In preliminary test, also the suitability of the dryer for the particular operation can be ensured. [2]

Evaluation of cost-efficiency of the drying process is strongly related to the material which is dried. Also, the energy source of heat used in drying plays a big role in operation costs. To make analyse for correct dryer for the need there is lot to be considered and this is only possible with extreme testing and getting valuable references. In the following list, collected some quantitative information that is needed for the drying technology suitability evaluation [2]:

- ✓ Throughput and mode of feedstock production (batch/continuous)
- ✓ Material properties (physical, chemical and biochemical) of the wet feed and desired product specifications and variability in feed characteristics
- ✓ Processing operations at upstream and downstream
- ✓ Target moisture content of the feed and product
- ✓ Kinetics of drying; moist solid sorption isotherms
- ✓ Quality parameters: physical, chemical, biochemical
- ✓ Safety; e.g. toxicity, fire hazard and explosion hazards
- ✓ Value of the product
- ✓ Automatic control needs
- ✓ The product´s toxicological properties
- ✓ Turndown ratio, capacity requirements and its flexibility
- ✓ Fuel type and cost, electricity cost
- ✓ Environmental regulations related to feed and operations

- ✓ Land area and space in plant

Technology evaluation is a long-term and material specific process. To cover the all operational needs of drying, one must be also aware of material specific and operational parameters listed in table 1. [2]

Table 1. Checklist for selection of industrial dryers [2].

Checklist for industrial dryer selection	
Physical form of feed	
	- Granular, particulate, sludge, crystalline, liquid, pasty, suspension, solution, continuous sheets, planks, odd-shapes (small/large) - Sticky, lumpy - Pre- and post-drying operations (if any)
For particular feed products	
	- Mean particle size - Size distribution - Particle density - Bulk density - Rehydration properties
Average throughput	
	- kg/h (dry/wet); continuous - kg per batch (dry/wet) - Expected variation in throughput (turndown ratio)
Fuel choice	
	- Oil - Gas - Electricity - Bioenergy* - Waste heat*
Inlet-outlet moisture content	
	- Dry basis - Wet basis
Chemical/biochemical/microbiological activity	
	- Heat sensitivity
Sorption isotherms (equilibrium moisture content)	
	- Drying time - Drying curves - Effect of process variables
Special requirements	
	- Material of construction - Corrosion - Toxicity - Nonaqueous solution - Flammability limits - Fire hazard - Colour/texture/aroma requirements (if any)
Footprint of drying system	
	- Space availability for dryer and ancillaries

*ModHeat technology enables usage of new kind of energy sources, which makes the technology unique.

2. MODHEAT® TECHNOLOGY

ModHeat (Modular Heating) is a modular and mobile industrial dryer developed by SFTec Oy. ModHeat enables economical and efficient drying of metallurgical sludges, and utilization of unused industrial waste heat to dry waste materials. Several pilots have shown that the ModHeat dryer is capable of handling many different types of materials that have been difficult to dry with traditional technologies. Steel industry sludges are normally composed of metal oxides with very fine particle size and high-water content. These by-products could be re-used if material handling costs could be lowered significantly. ModHeat is an important innovation for this sector as it will lower those major costs of material handling.

The ModHeat technology is based on a patented, breakthrough innovation of material circulation through changeable and stackable modules as a compact container construction. The material is fed in from the top of the dryer. Inside the container blades on identical modular layers moves the material forward from layer to layer while the hot air is blown in the opposite direction of the material flow. Power and capacity of the dryer can be modified by increasing or decreasing the number of the modules as well as changing the temperature of the blast air for material specific needs. The modular construction of the dryer enables the drying capacity addition based on the actual needs.

Hydraulic control of layers enables continuous control of the material flow, which allows the use of discontinuous and versatile temperature waste heat streams for drying. The operating principles of ModHeat is shown in Fig. 3. The dried material is fed out from the bottom of the container for further use. With the air flow temperature, material flow rate and material target moisture content the whole process is monitored and controlled.

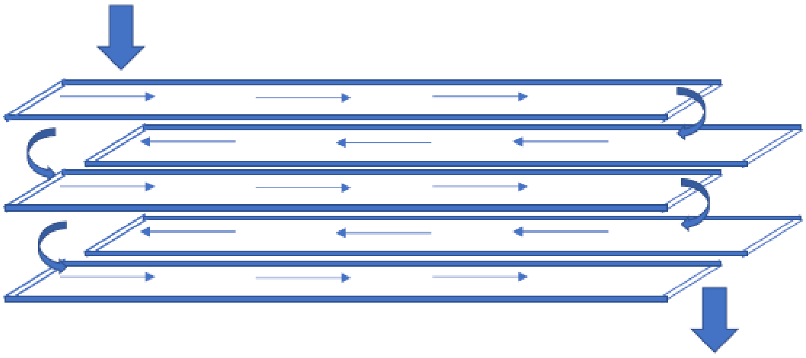

Figure 3. Operating principle of ModHeat dryer, © 2018 SFTec.

All the transport phenomena (mass, heat and momentum) and material properties are taken into account during drying, as the material moves and is mixed while processing. Continuous movement and mixing of the material guarantee the constant quality of dried materials. ModHeat-technology's benefit is its material specific convertibility, which makes the technology highly multi-functional.

2.1. ModHeat technology development and pilots

Behind the ModHeat dryer development is <10 years of R&D on technology, marketing and international business development. Innovation of ModHeat was formulated 2009 and basic technology research started. Research to prove feasibility demonstrated the significant potential of the innovation after which SFTec Oy was founded 2013 as a spin-off from the University of Oulu. The first ModHeat pilot unit (Fig. 4) was constructed in 2014 and the first customer paid pilot tests were made already in the same year with different kinds of materials.

Figure 4. First pilot of ModHeat technology, which is still used for small scale testing, © 2018 SFTec.

The full industrial scale pilot (Fig. 5) was built up in 2016 in a customer cooperation project. The first industrial scale the proof of concept tests was made with steel industry sludges within the same year. The full-scale pilot has enabled testing of different kinds of materials in the industrial scale with the technology, which have shown the wide feasibility of ModHeat technology.

Figure 5. Second pilot and full-scale of ModHeat technology on field test, © 2018 SFTec.

As a compact container structure, the drying area is maximized with the modular structure of the drying beds. The machine room is located to the other end of the container in the same package. In table 2 is shown the technical details of the industrial scale pilot - MHC12.

Table 2. The technical details of ModHeat industrial scale pilot dryer – MHC12.

Technical details of ModHeat	
Material requirements	The solid content over 10 % Particle size under 80 mm
Drying temperature	Under 160 °C
The amount of testing material	Minimum 20 m^3 (a truck load)
Physical dimensions	Dimensions of the dryer: 2,4 x 2,6 x 12,1 m Drying area: 70 m^2
Process control options	Fully automated Remote control possibility
Test costs	According to agreement
Transfer costs	Truck transport

2.2. Key advantages of the ModHeat technology

Modular construction, mobile usage and scalability: ModHeat dryer is a simple container construction with versatile options. Modular construction enables easy capacity scale-up, which is extremely difficult to realise with the industrial dryers available in the markets. Modular construction and standardized framework enable mass production of modules, which decrease production costs. Modular construction of the ModHeat dryer enables also short maintenance breaks and minor maintenance costs as the modules are removable. ModHeat is also available as a mobile unit, which enables new business opportunities in several industrial sectors. ModHeat is the first actually scalable dryer for all materials. ModHeat's scalability is based on the scalability of the internal construction of the dryer as well as on the possibility to combine dryer modules in a versatile manner (Fig. 6).

Figure 6. Example of ModHeat’s easy scalability, © 2018 SFTec.

Energy efficiency: Structure of ModHeat enables utilization of industrial waste heat which is currently not used – use of free energy. Waste heat utilization is a major benefit of the ModHeat dryer since up to 70 % of the life cycle cost of a convective dryer is normally due to energy [2]. Use of low temperature waste heat doesn't increase the size of the dryer infeasible owing to smart design, which also leads to reasonable investment costs. Well planned automation with right measurement variables, IoT solutions and construction of the ModHeat enables adaptive process control of production, which makes possible utilization of versatile waste heat streams.

Versatile material handling: To simplify the usage of the ModHeat dryer, it is fully automated. There are a variety of programs available for different kind of materials. ModHeat dryer is already successfully tested in industrial pilot scale with a variety of materials, for example chicken manure, wood chips, biogas residue and steel industry sludges.

3. DRYING OF STEEL INDUSTRY SLUDGES

The major problem with metallurgical sludges is that they have a moisture content of around 25 - 35 % and their physical properties are difficult for traditional dryers to handle. To enable utilization of valuable components of sludges drying is an essential process phase. New developed ModHeat dryer technology was tested for metallurgical sludge drying at first in pilot scale in 2015. In cooperation with a steel industry drying tests of blast furnace (BF) sludge and basic oxygen furnace (BOF) sludge was planned and accomplished.

At first in laboratory was analysed starting moisture contents of sludges, moisture content of the material during drying and optimal drying temperature of the materials. Laboratory analyses were done at the University of Oulu in the Laboratory of Process Metallurgy.

The starting moisture content of BF sludge was 22,71 % and for BOF sludge 26,52 %. The optimal drying temperature of sludges were measured with DSC-TGA analysis. Analyses of the samples were done in nitrogen atmosphere. Results of the thermogravimetric analysis (TGA) are shown as a function of temperature (°C) and weight change (%) in Fig. 7a. In the TGA diagram, the sharp weight loss under 100 °C shows vaporisation of unbound free water and surface water from the sludge samples (Fig. 7a.).

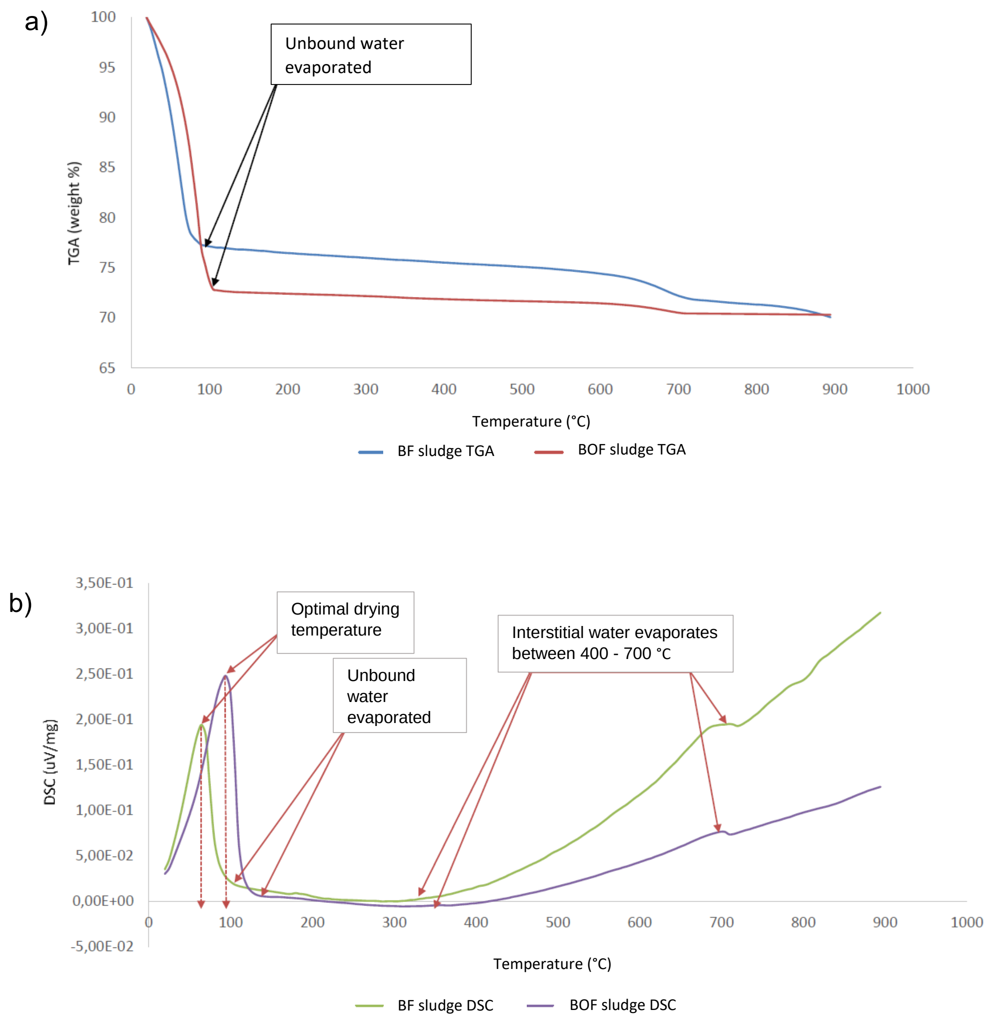

Figure 7. a) TGA -analysis and b) DSC analysis of BF and BOF sludge.

Differential scanning calorimetry (DSC) analysis measures the heat transfer (endothermic and exothermic) of reactions of the sample during heating. DSC results of BF and BOF sludge are shown in Fig. 7b as a curve of heat flux versus temperature. Based on the laboratory tests the optimal drying temperature for BF sludge is 70 °C and for BOF slag 95 °C. The amount of interstitial water in sludges is small, so the high temperatures are not needed for drying to achieve the target moisture content.

To test drying with the new ModHeat technology, at first the technology suitability tests were done in pilot scale. Sample size in the pilot scale was 40 - 60 litres and the tested materials were blast furnace (BF) sludge and basic oxygen furnace (BOF) sludge. The pilot tests with ModHeat pilot show that it is possible to efficiently dry wet and adhesive sludges in optimized low temperature (under 100 °C) conditions in reasonable time. The adhesive nature of sludges did not hinder drying and the material moved in the process as planned. Samples of converter sludge before and after drying are presented in Fig. 8.

Figure 8. Converter sludge before and after drying, © 2018 SFTec.

The testing continued after the pilot scale testing with an industrial scale piloting. The industrial scale tests with the ModHeat – MHC12 (technical information above Tab. 2) pilot were run at the steel plant facilities. During the test campaign 80 tons of BF, BOF and sludge mixture were dried. Materials starting moisture content changed depending on the source of material, was it excavated out from the storage pile or came straight from the factory, between 20 to 31 %. The test material was dried to < 10 % moisture content.

Industrial scale drying tests of metallurgical sludges were the first large tests of ModHeat technology. Technology showed its potentiality as the sticky material dried moved as planned and the material properties did not hinder drying. The high specific gravity of these metal bearing materials is one of material properties effecting on technical design of the dryer in the future. At the same time was also tested utilisation of waste heat from slag as heat source of drying of which some results more up next.

4. RECOVERY OF HEAT FROM SLAG AND DRYING

ModHeat technology together with SFTec Oy´s another innovation RecHeat (Recovery of Heat from slag) forms a combined technology solution to increase steel industry material and energy efficiency. RecHeat is an innovation to recover heat from slag as low-price and simply as possible. Slags are generally processed to a by-product without heat recovery, which means ~1,5 GJ wasted energy per ton of slag. Heat recovery from slag by RecHeat enables its utilization as a free energy for drying.

The RecHeat is a new innovative and simple heat exchanger solution for slag heat recovery. The first prototype of RecHeat technology (TRL 4) is already tested at the steelwork in an industrial scale (Fig. 9.). Today in many cases steelmaking slag is simply poured on the ground or gathered in pots before being poured on the ground in the separate location. A traditional approach to control the cooling rate of the slag is water quenching, which consumes huge amount of water and fails to recover the heat of the slag.

Figure 9. RecHeat and ModHeat concept in the field test, © 2018 SFTec.

RecHeat and ModHeat combination was tested in 2016 at a steel works in Finland. Heat recovery from liquid slag with RecHeat technology is based on the metal structure with a large heat transfer area, on which the liquid slag is poured on. The liquid slag on RecHeat heats up the air flow, which is blown through the metal structure. The metal structure works as a kind of tube heat exchanger, and no water is used.

Based on the pilot tests of RecHeat and the modelling results the heat exchanging area of RecHeat was too small to maximize the heat recovery from the slag. A new scale-up version of RecHeat will be designed and constructed by SFTec in 2019 and tested as a part of RFCS project ECOSLAG. Heat recovery from the slag also effects the cooling of slag, and consequently also the quality of solidified slag. The new scale-up version will be tested to optimize the structure and heat recovery efficiency of the technology.

Together ModHeat and RecHeat innovations form a new KIS-ECO (Keep it Simple – Eco Logical Solutions) concept, which enables the heat recovery from slag and drying of material streams. The first industrial scale field tests have shown the potential and need of the solution. The KIS-ECO concept enables controlled cooling and heat recovery from slag without the need for water cooling and utilizes the recovered heat. The controlled cooling of the slag also provides new possibilities to optimize the solidified slags properties e.g., leaching behaviour and free-lime content. With the new innovative solutions, there are possibilities to proceed in the field of circular economy and increase the material efficiency of steel industry further.

5. CONCLUSIONS

Processing of different kinds of low value side streams must be cost-efficient and in many cases drying is one of the first unit operations needed. Drying is a complex unit process including simultaneous and coupled heat, mass and momentum transport in the matter media. In direct convection dryers, like ModHeat technology, energy is transferred as heat from heated air to the wet material. The simple target of drying is to reduce the moisture content of the dried material.

Metallurgical sludges and their valuable components are reusable after drying. High moisture content and adhesive nature of material hinder drying with traditional drying technologies and sludge reutilization today. The pilot tests (small and industrial scale) have shown that ModHeat dryer is capable of handling these hard to handle materials. The ModHeat dryer as a compact container construction enables its utilization in variety of locations with minimum environmental engineering. Scalability of the ModHeat technology makes it possible to use for different types of needs.

Currently industrial waste heat is not utilized maximally, and sludges are landfilled without drying. SFTec's innovative dryer is a new technology which enables in the future drying of steel making sludges locally and enables the recovery and reutilization of valuable materials from wet by-products. It can also utilize the unused waste heat capacity of slags for drying of sludges and so enables re-utilization of dried solids.

SFTec’s aim is to make a difference in material and energy efficiency with concrete technological solutions. Our mission is to create innovations for sustainable and resource efficient material handling and to increase the cost efficiency of processing of side streams and waste heats. Innovative solutions are the key for the future development and this work has started. Next step is standardization of the technologies and long-term industrial reference piloting.

REFERENCES

---

[1] Delgado, J.M.P.Q., Barbosa de Lima, A. G.(eds.). Drying and Energy Technologies, Advanced structured materials. Springer International Publishing Switzerland 2016, ISSN 1869-8441(Electronic). p. 228.

[2] Mujumdar, A.S. Handbook of industrial drying. Third edition, Taylor & Francis Group, LLC (2006). p. 1287.

[3] Datt P. (2011) Latent Heat of Vaporization/Condensation. In: Singh V.P., Singh P., Haritashya U.K. (eds) Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. Available from: https://doi.org/10.1007/978-90-481-2642-2_327. Referred 09-11-2018.